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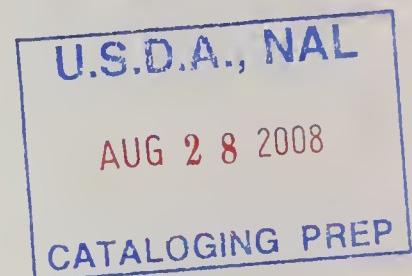
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PACIFIC SOUTHWEST
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A MODEL FOR EVALUATING WILDLAND MANAGEMENT FOR FLOOD PREVENTION

Henry W. Anderson



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FOREWORD

This paper attempts to summarize the experience and ideas resulting from several years of research in flood analysis and evaluation of flood prevention. Its purpose is to stimulate thinking among those interested in conducting studies basic to flood hydrology or in analyzing flood causes.

The paper reviews flood cause and flood source analyses in the literature; synthesizes these with additional physical considerations so as to outline the elements of a model expressing floods from watersheds as a function of the meteorological conditions and watershed topographic characteristics and land conditions; suggests steps in model formulation and analysis needed to evaluate the effects of these characteristics and conditions on flood sizes by multi-variable analysis; and outlines some applications that can be made of the model in identifying flood sources, in designing structures, and in evaluating flood prevention needs and effectiveness.

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FOR FLOOD PREVENTION

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FOR FLOOD PREVENTION

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Floods don't just happen, they are made--or at least the watershed conditions are made that change little floods into big floods and rare floods into frequent floods. No one questions this statement in principle, but our knowledge is scant as to what extent it is so and what watershed management could do to prevent floods.

Why is this knowledge so inadequate? We have had many floods to study. We have had almost every kind of floods occurring under a wide variety of watershed conditions. The difficulty lies in isolating the causes of floods. This remains true despite a vast storehouse of basic data on rainfall and temperature, topography and geology, forest types and densities, forest and brushland fires, and histories of logging, grazing, road development, and most other land uses. But this difficulty need not be a barrier. We can analyze these data to give us guides on how to manage for flood prevention and where such management will be the most effective. A start of such analyses has been made for southern California and for Oregon and Washington (Anderson, 1949; Anderson and Trobitz, 1949; Anderson and Hobba, 1959).

This paper outlines some of the processes of flood hydrology and proposes an analysis to evaluate flood prevention in the northern California wildlands. Our point of view is strictly that of floods and their prevention. However, we should emphasize at this point that some uses of land which tend to increase floods may have benefits of increasing total water yield (Goodell, 1959; Anderson, 1960).

We will (1) review flood cause and flood source analyses in the literature; (2) synthesize these with additional physical considerations so as to outline the elements of a physical model expressing floods from watersheds as a function of meteorological conditions, watershed topographic characteristics, and land conditions; (3) suggest steps needed to evaluate the effects of these characteristics and conditions on flood sizes by multi-variable analysis, and, finally; (4) describe some applications that can be made of the model in identifying flood sources, in designing structures, and in evaluating flood prevention needs and effectiveness.

CAUSES AND SOURCES OF FLOODS

A flood results from a number of inter-acting causes operating on a number of source areas at the same or different times. Differences in meteorological events and in the physiographic and geologic characteristics of watersheds bring about wide differences in flood sizes. Other causes of differences in floods can be attributed to differences in the type of vegetation and the condition of vegetation brought about by accident or by land use. To evaluate how various flood causes affect the flood size, we will set up a model and evaluate its performance.

THE MODEL FOR STUDY

What do we mean by a model? Is it a physical model or a mathematical model? It is both--physical in the sense that watersheds can be seen and measured, and mathematical in the way we use the measurements in evaluating and manipulating the model.

Let us design a model. Since we want to study floods from entire watersheds, we will need a large area of land in which to "build" our model. Take California, north of the Tehachapi Mountains. We will "build" a watershed in which both rain and snowmelt floods will occur, one that extends from low elevations to high. Luckily, several such watersheds already exist, such as the San Joaquin River watershed. Next we want to select another watershed that receives higher rainfall than the San Joaquin; perhaps the Trinity River in the North Coast Range will do. We want a forested watershed, a non-forested one, and so on. We find that watersheds with each of these characteristics already exist, scattered about the map and representing all the characteristics and conditions we would logically want to manipulate in a model if we had actually built one. For years this model has been operating automatically, integrating all causes of floods. Our problem is to isolate and evaluate those causes.

The mathematical part of our model now comes to our aid. Statistical tools have been developed for evaluating complex models. These tools include multivariate analysis, regression analysis, and covariance analysis.

The model we choose depends on the scope of our present knowledge of the hydrologic processes and what affects them, of the art of analysis, and of the data which are available or obtainable. We choose a model which will (1) extend our knowledge and allow ready adjustment and application with the advent of new knowledge, and (2) be rational insofar as possible. We want to let processes be separately evaluated rather than hidden with others in an index, let physical rather than statistical considerations determine the functions, and let units be standard with real zeros rather than ratios or scales with built-in constants. A rational model and real variables will allow us to extend present data and predict with some confidence the frequency with which various topographic areas and land conditions contribute to floods.

The model must be capable of being tested statistically if not experimentally; the possibility of chance effects must be assessed, and statements of reliability and probable errors provided. Then, we and others may judge the validity of the model and of interpretation made by manipulating the model.

THE HYDROLOGIC PROCESSES

In evaluating the flood potential of watersheds and the flood sources within them we must consider these hydrologic processes: (1) the supply processes--precipitation and its characteristics; (2) the storage and detention processes--surface, soil, and channel; and (3) the loss processes--interception, evaporation, and transpiration (and in some places, groundwater losses or deep seepage) (Anderson, 1960).

These hydrologic processes are represented by variables which express their effects in quantitative terms. The variables affecting the processes include (1) specific expressions of the precipitation--such as amounts, and characteristics of rain-snow and snowmelt; (2) expressions of the physical conditions on the watersheds--such as area, elevation, orientation, slopes and aspects, geology and soils as they affect storage, detention, and loss; and (3) expressions of the biological conditions on the watersheds--such as vegetation type and condition, land use, roads, and fire history as they modify the above hydrologic processes. The steps in our analysis of floods consist of determining the particular expression of each variable that we use and our choice of the interactions and functions for study.

ANALYZING FLOODS

We take these specific steps in analyzing floods: (1) the selection of the unit of study, the dependent variables, the independent variables (flood causes), and the data for analysis; and (2) the choice of an analytical model (functions of the variables).

THE UNIT OF STUDY

The storm or meteorological event and its resultant flood discharge determines the unit of study. Floods generally are of two types: short duration floods in which flood-impact damages occur, and long duration floods in which inundation damage results.

THE DEPENDENT VARIABLES

A frequently used expression of flood size is the maximum discharge associated with a storm, snowmelt event, or annual event. It has proved to be the most useful in evaluating flood impact damages and in designing structures such as culverts and dam spillways.

In assessing inundation damages, flood water loss, and reservoir storage, longer duration flows are commonly used, such as the 1-day flow, 10-day flow, 30-day flow, or 90-day flow (Kuhnel, 1949; Corps of Engineers, 1958).

THE INDEPENDENT VARIABLES

Some important independent variables affecting flood size will now be described, their measurement or estimation outlined, and their operational definitions suggested.

Meteorological Variables—Rain and Snowmelt

How much rain and snowmelt contributes to a flood depends on the amount and intensity of precipitation prior to and during the event, the distribution of rain versus snowfall during the event, the accumulated snowpack and its condition prior to the event, and the meteorological conditions causing snowmelt (Anderson, 1958; Anderson and Hobba, 1959).

The precipitation amount is an important meteorological variable affecting flood size; yet we have difficulty in determining this variable in an accurate, unbiased way for mountain watersheds. Raingages usually sample only a small part of the variation in terrain within watersheds. These same raingages may catch a rather poor sample of the storms even where they are located, particularly during most snow storms and during high winds in rain storms (Hildebrand and Pagenhart, 1954). We can consider two solutions.

One solution includes the adjustment of precipitation for terrain, using only those storms in which rain occurred at all elevations and wind was not excessive. The methods of Spreen (1947) and Burns (1953) seem appropriate, if applied only to these particular storms.

A second solution has been used by the Corps of Engineers and the California Department of Water Resources. It utilizes the annual streamflow from watersheds (where groundwater loss is negligible). The precipitation is taken to be the sum of the measured streamflow plus an estimated evapotranspiration loss from the watershed. The total precipitation so determined is then distributed in the watershed by using known precipitation of some points and simple precipitation-elevation relationships. This method would be expected to give a better map of annual precipitation than simple application of the raingage network. We could probably obtain an even better map by combining this method of determining annual precipitation with Spreen's method (1947) in distributing the precipitation to the parts of a watershed.

If we have a mean annual precipitation map for an area, we can often measure storms or other short-term precipitation with fewer gages than would be required for equal accuracy without such maps. For each storm the precipitation can be expressed as a percentage of the mean annual precipitation at the gages. Isopercentile lines are drawn, and the areal precipitation is determined as the weighted average of the mean annual precipitation of any unit of area and the isopercentile of the storm for that area (Anderson, 1958). In this way the precipitation amount in relatively small areas and over rather short periods of time may be more accurately estimated than otherwise.

Rain versus snowfall.--Whether the precipitation occurs as rain or as snowfall may be just as important as the amount in determining the size of the flood. The area in watersheds where rain rather than snow fell during a storm has been evaluated by using the air temperature during the precipitation and the normal lapse-rate of temperature with elevation (Anderson, 1958). We took the rain area as that part of the watershed where the air temperature was higher than 32°F. during the maximum precipitation period of the storm.

Elevation has been used as a variable in some studies as an index of the rain-snow characteristic of precipitation (Todd and Ateschian, 1956; Neff and Sheffer, 1959). It proved effective in studies where the size of a flood of given frequency was to be determined. However, if we are evaluating individual flood events, the specific characteristics of rain, snow, and snowmelt should usually be used.

Snowmelt frequently contributes significantly to flood size in California, particularly in major floods (Hall, 1943). The contribution of snowmelt depends upon the snow being ripe, that is, in a condition in which the addition of heat will cause the release of melt water. Where snow has not ripened, a snowpack may actually reduce the amount of effective rainfall by absorbing rain (Himmel, 1951). The temperature antecedent to the flood-causing event has been found useful as an index of the ripeness of the snowpack (Anderson, 1958; Anderson and Hobba, 1959). If the snow is ripe, the variables affecting the amount of snowmelt are these heat sources: heat in rain and the radiative, conductive, and advective heat, determined by the air temperature, humidity of the air, and wind velocity (Corps of Engineers, 1956). In a 5-inch rain on a snowstorm at the Central Sierra Snow Laboratory in January, 1953, 40 percent of the runoff was attributable to advective melt water (Boyer, 1954).

The interaction of snowmelt variables and forests can not be ignored. The forest condition may affect floods by changing the snow area, the snow ripeness, and the opportunity for radiative and advective snowmelt.

Watershed Recharge and Storage Variables

Just as reservoirs differ widely in their storage capacity, so do watersheds, both between watersheds and from time to time in the same watershed. The amounts of such storage and the variation between watersheds may be illustrated by data from the Sierra west side during September through December, 1937 (McGlasson and Briggs, 1939). Storage (and evapotranspiration) reached a maximum in the Feather River Basin. About 20 inches of the 30 inches of precipitation never appeared as runoff (Anderson, 1961). Most of this retention storage occurred prior to the December 1937 flood, so that runoff in that flood was high, 6 to 10 inches. In contrast, the total September through December retention in the Kings River basin was about 10 inches; however, only 1-1/2 inches of this storage was depleted prior to the 1937 flood so that over 8 inches of the precipitation during the flood was stored in the watershed. As a result the Kings River in the December 1937 flood had a rather low flood runoff of only 1-1/2 inches.

Soil and rock storage of water has an important effect on floods. Deficit of such storage makes a direct subtraction from the precipitation which might cause floods. Certain vegetation types tend to create large soil moisture deficits, so vegetation differences would be expected to be important in affecting flood size.

Soil moisture deficit in fall has been estimated to range in major river basins of the Sierra west side from 4 to 10 inches (Anderson, 1961). Greater differences surely occur in smaller watersheds and between parts of watersheds. In natural forest sites soil moisture deficits have been found to range from 3 to 17 inches (Knoerr, 1961). When vegetation is removed, as in logging or by brush removal, soil moisture deficits have been found to be from 1 to 8-1/2 inches smaller (Anderson and Gleason, 1960; Anderson and Richards, 1961).

Rock storage and retention of potential runoff waters may range from 45 inches or more in highly fractured igneous rock and unconsolidated alluviums to negligible amounts in granite batholith. A wide difference in flood peak runoff has been found to be associated with geologic rock types between watersheds (Anderson and Hobba, 1959). Evaluations to date have been on empirical class-type variables, but we can expect refinement in these classes and ultimately rational variables expressing rock storage and retention.

Lake, stockpond, and reservoir storage are not as significant as soil moisture and rock storage, but they can still have important effects on flood sizes. In large watersheds of the Sierra, lakes have been found to occupy as much as 4 percent of the watershed area (Richards, 1961). For small watersheds, lake and reservoir storages may be even more important and require evaluation in flood cause studies.

Snow storage at high elevations during almost all events and at lower elevations during some events can have important effects on flood peaks. Snow storage is a primary cause of reduction in peaks during rain-caused floods, yet it may subsequently augment snowmelt flood runoff. Wide differences in snow storage are associated with differences in the terrain variables: slope, aspect, exposure, and curvature. For example, as much as a 23-inch difference in water stored in a snowpack was associated with differences in slope, (Mixwell et al., 1952; Anderson and Pagenhart, 1958). That such wide variations in snow storage will affect floods seems evident. Much information needed for evaluation of snow storage is on hand, thanks to the work of the Cooperative Snow Investigations of the Corps of Engineers and Weather Bureau and of the Cooperative Snow Management Research Program of the Forest Service and the California Department of Water Resources.

Infiltration of rain and snowmelt into the soil is necessary if soil or rock storage is to be utilized. The infiltration concept of runoff has been outlined by Horton (1937, 1945). Application to watersheds of the Pacific Coast has been negligible, largely because of the complexity of the model of streamflow which would be entailed in its use. Infiltration varies widely in space, in time, and with land use. In the present

state of knowledge infiltration considerations guide our choice and expression of the precipitation, soil, and land-use variable; in the future, inclusion of infiltration in a more rational form may be expected.

Delivery Variables

Flood size depends on the rate of delivery of water as well as on the total amount of water. Therefore we are concerned with the detention of water and the velocity of water flow from watersheds. Detention of water on the slopes occurs in three forms: depression storage, surface detention, and subsurface detention. Depression storage is that water detained on the slope surfaces in temporary pools. Surface detention is that surface water enroute from the watershed slopes to channels at any time. Subsurface detention occurs as pondage in soil and rock voids which have widely different release rates and travel-paths to channels. Similarly, water may be detained in the channels or in flood plains enroute from major watersheds. Thus, broadly considered, the detention and flow of water from watersheds may be influenced by the characteristics of the slopes, the soils and geology, the channels, and the flood plains.

Slope and aspect variables affect delivery of flood waters primarily through their effects on depression storage, surface detention, and rate of flow. Depression storage is affected most by the steepness of slope and the roughness of the slope surface. Surface detention is affected by roughness, steepness, as well as length of slope. Horton (1945) has shown some relationship of roughness to depression storage, surface detention, and runoff. He has also given many relationships of depression storage and surface detention to slope steepness. They should prove useful in setting up variables for testing the effects of slope conditions on flood runoff. Interactions of the slope variables, the meteorological variables, and the biological variables will determine the quantity of depression storage and surface detention during storms.

Slope and aspect also affect flood runoff through their effects on evaporative losses and snow storage. Snow storage and rate of melt have been shown to be related to the solar energy received on slopes (Anderson and Pagenhart, 1957). Horton (1932) developed the concept of the equivalent plane of a watershed which has a single-valued expression of watershed slope and aspect. The north-south component of Horton's equivalent slope was found related to both rain-on-snow floods and snowmelt floods (Anderson and Hobba, 1959). Larger flood peaks were associated with north-facing watersheds.

Area and elevational variations between watersheds modify flood runoff. Both are much misused and misinterpreted variables. Most of the variables which we neglect to put in our analyses and many of our mistakes in choice of functions hide in the "area" variable, which has been called "the devil's own variable" (Anderson, 1957).

Similarly, elevation is better expressed in terms of the process which it affects rather than as an index of a complex of processes. Elevational distribution of rain versus snow, snowmelt, geology, and vegetation may be expressed directly as variables rather than hidden in a variable which we label "elevation" (Anderson and Hobba, 1959).

Channel variables modify flood runoff by their effects on channel storage and the velocity of runoff. Velocity in turn affects the timing of runoff from various parts of a watershed and the buildup of flood peaks.

Channel storage affects the shape of the runoff hydrograph. The amount of channel storage can be estimated by methods suggested by Horton (1936, 1937, and 1945). The steepness of channel, length of channel, stream order numbers, and roughness of channels all help characterize the channel storage conditions.

The channel conditions that affect the rate of delivery of water also include the pattern of channels in a watershed. Anderson and Trobitz (1947) and Anderson (1950) related flood sizes in southern California to Horton's (1945) length, slope, and bifurcation ratios. Channel characteristics have been expressed in different ways by other workers. Gottschalk (1950) expressed channels simply as Horton's (1945) channel density variable. Others (Todd and Ateshian, 1956; Schumm, 1957) have employed the slope of the main channel in such variables as the relief ratio and the difference in elevation between the gaging station and highest points in the watersheds.

Although Horton's classic variables for expressing channel characteristics will certainly continue to prove useful, some newer characterizations also deserve consideration (Miller, 1953; Melton, 1957; Strahler, 1957; and Skykind, 1961). Recently, Busby and Benson (1960) developed an easy method of computing the length of the mean flow path from various parts of watersheds. It seems obvious that the standard deviation, kurtosis, and skew of the distribution of path lengths from various parts of the watershed will prove to be intimately related to the shape of the hydrograph and hence to the flood peaks. On the whole, the variables for evaluating the effects of channel conditions on flood runoffs seem to be adequately developed.

Flood plain variables may have to be taken into consideration when floods from large watersheds are being studied. Channel capacities (Leopold and Maddock, 1951), overflow areas, crops and their management, roads and other impervious areas, and flood prevention structures may have to be expressed as variables. The most promising approach is to express the variables as they affect the supply, storage, and detention of flood runoff at the flood plain.

Sediment Bulking Variables

Flood discharges are not all water--sediment suspended in water, bedload moving along channel bottoms, and deposition of sediment in channel all increase flood height. Bulking effects reach a maximum during the flood peak. Bulking of discharges has been measured as high as 100 percent.^{1/} Suspended sediment bulking has contributed 15 percent of the flow volume in Sespe Creek, California, following the 1954 fire.^{2/} In the upper Cuyama basin, a small thunderstorm produced suspended sediment concentration of 30 percent of the total volume.^{3/} Although such high concentrations of sediment are special cases, sediment is often an important contributor to flood peak discharges.

Because flood causes and sediment causes tend to be closely linked, a good practice is to study them at the same time (Anderson, 1949; Anderson, 1954; Anderson and Hobba, 1959). In this way variables and functions of flood causes, such as peakedness of flows, help explain variation in sediment production; variables of sedimentation, such as soil erodibility, help explain bulking of flood flows with sediment.

Biological Variables

Biological variables affecting floods act chiefly through the vegetation that exists on watersheds, the use that is made of that vegetation, and the condition of the vegetation. These modify the supply, detention, and losses. Differences arise in the amounts of precipitation infiltrating into the soil, water stored in the soil, and evaporation and transpiration losses from the soil. These may change the delivery of water from watersheds by affecting the depression storage, the surface detention, and the surface versus subsurface path of runoff waters.

These biological variables may be expressed in two ways: as variables of forest types, such as grass or woodland, cultivated or barren, and burned-over or logged; or in terms of their known effects on some hydrologic processes, such as infiltration capacities, interception and other evaporative losses, and storage and detention characteristics associated with each vegetation type.

Vegetation types when used as variables would usually include these classes: forests of various densities, brushland areas, woodland and grass areas, and cultivated areas. These classes may be further

^{1/} Preliminary report of sedimentation following the December 1953 fire and January 1954 storm. Los Angeles County Flood Control Dist., 1954.

^{2/} From Annual Report of Santa Clara Water Conserv. Dist., Santa Paula, Calif., 1934-1935.

^{3/} Measurements made by Clark H. Gleason, Upper Cuyama Tributary, converted to percent by volume by using density of 2.65.

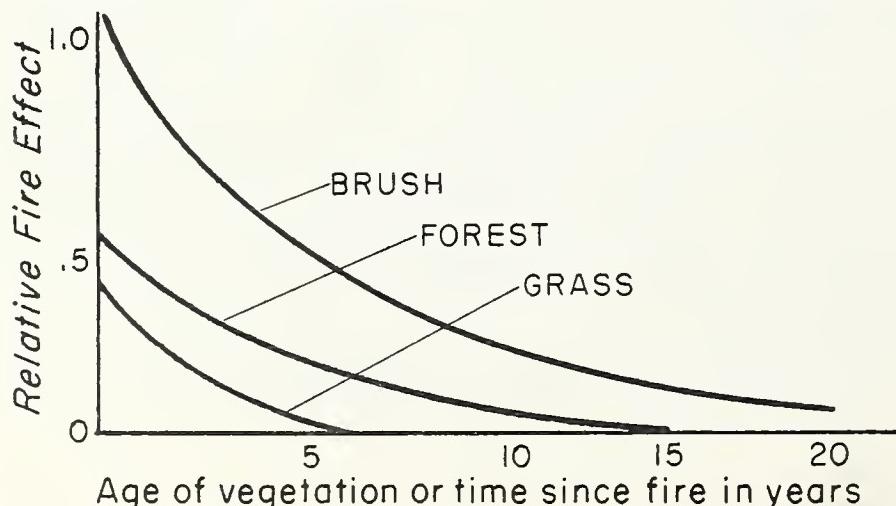
refined by the physical expression of them. For example, a forest may be expressed in terms of its age and stocking, and a cultivated area in terms of bare cultivation versus other cultivation (Anderson and Hobba, 1959). Use of these class-type variables in analysis has become quite easy with the development of electronic computers.

Land use and condition may be expressed in terms of the age and density of the various vegetation types existing on the watersheds. Differences in these are brought about by a variety of differences in land use--forest and brushland fires, logging and road building in forest lands, fire and grazing in woodlands and grassland areas, and cultivation and urban development.

Forest and brushland fires have a major effect on vegetation and we may hypothesize that they also affect floods. Forest and brushland fires may be expressed in terms of their areal extent, their intensity, the lapse of time since the fire, the damages in suppressing the fire, and the post-fire treatments of the burned areas.

We seek certain relationships between fires and the sizes of floods. In doing this we may wish to test various expressions of fire variables, such as:

1. Fire effects are directly proportional to the amount of burn, inversely proportional to the age of burn (up to some maximum age), and directly proportional to the intensity of the burn (with intensity determined by the meteorological conditions or burning index).
2. Fire effects depend on materials left on the site rather than on what was destroyed, so that exposed soil areas may be the best index.
3. Fire size is in itself an index of the intensity of burn and the time until vegetation recovers. Small fires seed in rapidly. Needle or leaf-fall covers small or light-intensity burns.
4. The time it takes vegetation to recover after a fire varies according to vegetation types. Grass may require 2 years, brush 10 years, and forest 20 years.
5. A depletion type curve best expresses the relationship of each fire to fire effects.



6. Fire effects depend upon the storm intensities which occur after the fire and hence tend to compact or remove surface soil. The amount of precipitation occurring at intensities greater than one quarter inch per hour is weighted inversely by the number of years lapsed since the fire.

We can test a number of these hypotheses of how we can best index fire effects on floods.

Treatment of burned areas may greatly affect flood runoff following fires. Variation would be expected to occur with differences in such treatments as salvage logging, grazing, seeding grass, and reforestation.

Thus, the effect of fires on flood peaks would be different depending on the characteristics of the fire itself, the vegetation in which the fire burned, the types of storms which follow the fire, and the treatment of the burned area. Each of these factors must be evaluated if the effects of the fires on flood peaks is to be accurately appraised.

THE SELECTION OF DATA

Selection of Watersheds

Following the selection of variables which are expected to affect flood size, comes the selection of the data for analysis. We must select the watersheds to be studied, the meteorologic or storm events producing the flood, and the analytical model.

Watersheds to be used in the study should represent the extremes of all combinations of characteristics to be evaluated--characteristics which affect the supply, storage, and delivery of flood waters. The streamflow records from the selected watersheds should not have unknown variation in reservoir storage or operation, arbitrary changes in the ratings of the stream, or widely different stream gaging sites during the period of record to be used. Watersheds should have streamflow records encompassing years with wide variation in flood sizes, hence long periods of record will usually be advantageous. For evaluating non-linear effects of variables on floods, we need intermediate values of watershed characteristics rather than only the extreme values.

Selection of Meteorological Events and Storms

Again, we select data which have a wide range of the characteristics to be evaluated: storms in which precipitation amounts are small, intermediate, and large; storms in which rain occurred throughout almost all watersheds; storms in which part or all of the precipitation was snow; storms or snowmelt events occurring on wet and dry watersheds; and meteorological conditions in which snowmelt was likely to have contributed widely different amounts to the flood. In making these choices, we have found a selection table helpful (Anderson, 1958). In this way, we could balance the distribution of events of various characteristics so as to destroy internal correlation of the variables.

The watersheds and the meteorological events are chosen. Then we determine from available records the flood sizes associated with those events from these watersheds. Following this, we set up the analytical model relating flood size to the flood cause variables.

THE ANALYTICAL METHOD

Several methods of analysis have proved useful in relating floods to cause variables. Multiple regression has been found valuable in studying floods (Anderson and Trobitz 1949; Anderson 1949, 1950; Todd and Ateshian, 1956; Anderson and Hobba, 1959; Neff and Sheffer, 1959). Recently other forms of multi-variable analysis have been adopted in some studies, such as multi-variate analysis by Snyder (1961) and restricted regression analysis by Harris et al. (1961). Where watersheds are to be tested by groups, or storms and meteorological events are to be analyzed by groups, covariance analysis has been found useful in testing the consistency among regression equations (Anderson and Hobba, 1959). In all of these analyses, we relate the end product--flood size--to the cause variables, evaluating the independent effect on floods of each cause and the combination of causes.

THE SPECIFIC MODEL

We select a specific model which rationally relates flood sizes to the dependent variables. Usually the relation is taken to be in the form of linear quadratic, joint linear, or logarithmic relation. It has been said by some that only the logarithmic relation is appropriate for floods, because they depend upon proportional contribution of each variable (Chow, 1954). Other analyses have considered variables only in their linear, quadratic, and joint linear effects (Harris et al., 1961). Rational analysis of the physical phenomena occurring--threshold values, true zeroes, and depletion and accretion phenomena--may suggest other models and transformations in data. Probably our best solution is to select the form which is simplest and the most appropriate to the end use of the results obtained. We then test this form for any deviation from the simple relations and for joint effects by comparing the predicted values with the actual values. Again, electronic computers make such comparisons relatively easy to perform. Also, we may wish to explore (within rational boundaries) alternative forms of the relations between flood size and our prediction variables.

TESTS OF THE ANALYTICAL RESULTS

The analytical results may be tested in two independent ways. In the first test, we express the error obtained from the analysis itself: the standard error of estimate, the test of the significance of the variables, and the comparison of flood values predicted by the model with the measured flood discharges used in the analysis. In the second method, we compare predicted values for events and watersheds not used in the analysis with measured floods. The second is considered a more valid test of the degree of prediction and the control possible through use of the variables included in the analysis. Both forms of tests should be made and their results given as a part of the evaluation report.

A word of caution is provided here in avoiding the tendency to let the statistics determine the model. The choice of arbitrary levels of rejection of variables, such as the 5 percent level, needs serious questioning (Anderson, 1957). After we have introduced a variable into our model on rational considerations, dropping that variable (in effect substituting zero for its regression coefficient) can hardly be expected to make our model more rational. The testing of a large number of variables or functions of variables expressing the same thing, and accepting the one of highest significance, gives an invalid sense of accuracy. As a minimum, each try should reduce the degrees of freedom by one (Anderson, 1950). No statistical manipulations of a single set of data will yield both improved hypotheses and valid tests of those hypotheses. In general, statistics is the hydrologist's tool; the hydrologist should not be the victim of statistics.

APPLICATION OF THE ANALYSIS RESULTS

The analysis results have wide applications in studies of flood frequencies, flood prevention, and the design of flood water structures. Other applications will be found in studies in which floods themselves are considered cause variables, such as in sedimentation, inundation, and urban development studies.

FLOOD FREQUENCIES

The analysis results can be used in the extension of flood frequencies based on long-term meteorological events and their relation to floods (Anderson, 1949). For such studies we can use the effects of differences in land use and treatment on floods to adjust floods previously measured to the expected sizes of these same floods under present or any projected land use conditions. Flood sizes can be computed for areas or for periods in the past when the meteorological variables were measured but flood sizes were unknown.

FLOOD SOURCES

The analysis results may be used to appraise flood sources. We can compute the frequency with which various parts of watersheds having specific characteristics of elevation, slope, and land-use condition contribute to floods (Anderson and Hobba, 1959). Thus, we can determine the relative flood potential of each area of a watershed. Such evaluations are the first guide to the need for care in management of certain areas for flood prevention.

FLOOD PREVENTION

The model can be used to evaluate the effectiveness of such flood prevention measures as reducing the amount of burned area, planting forest sites, converting brushlands to forest or grass, and other land management practices which affect the variables in the analysis. Contrary wise, the need for other types of flood control, such as dams and channels,

may be forecast because of projected changes in land use in a given watershed. These needs can be evaluated from the analysis results.

STRUCTURAL DESIGN

The analysis results can be used as a guide in designing structures to transport or control flood waters. How large should culverts under roads be to have a given factor of safety? What runoff intensities may be expected from areas cleared for forest roads, airfields, or power lines? If we log forest in a manner to increase water yield or delay snow-water melt, what are the resultant effects on flood runoff volumes which must be handled?

CONCLUSIONS

We have analytical methods and data to relate watershed conditions and characteristics, expressed in physical terms, to flood runoff. Flood frequency analyses can be improved, flood sources appraised, and the effects of management on floods evaluated (Anderson, 1961). This information will help those who must make management decisions on watersheds do so with full knowledge of the flood consequences. Alternative methods in management may be selected which will meet necessary flood prevention goals, and management may be applied to repair watershed conditions whose consequences are unacceptable.

Success in developing flood control programs and marshalling resources for such programs depends on good physical evaluation of floods. Resources will gravitate to the programs which can show that the practices to be applied are put into use only where they are most needed and will be the most effective. Programs will obtain support when their effects can be accurately predicted, and when alternatives can be shown to be less effective. Then, too, managers will obtain the greatest compliance with programs and cooperation in them. Competent physical evaluations of flood prevention programs will guide the manager in the best choices open to him. With such guidance, he can marshal resources and apply the most efficient management.

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